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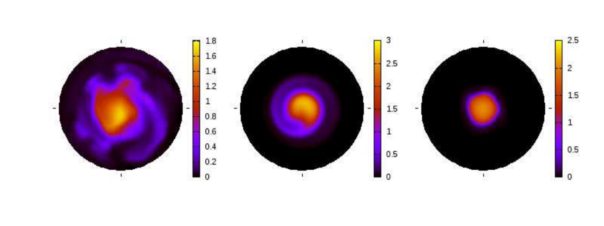
Comparison of drift-fluid modeling with experimental observations at NAGDIS-II - studies on intermittent cycles

PMIF, Oak Ridge, 10 Sep 2013 | D. Reiser, N. Ohno, H. Tanaka, L. Vela

Previous Studies - Impact of Plasma Source

Studies on linear devices - PMIF 2012



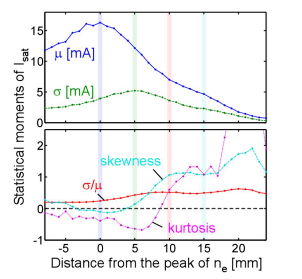
Plasma dynamics in linear devices might be strongly intermittent!

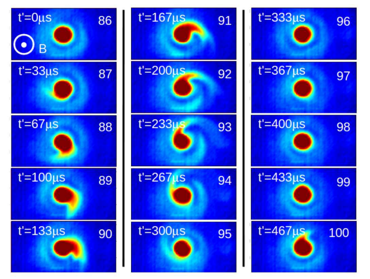
Geometry of plasma source plays important role!

NAGDIS-II

Several similarities with NAGDIS-II experimental results have been found

H. Tanaka et al., Contrib. Plasma Phys. 50, 256 (2010) & 52, 424 (2012)



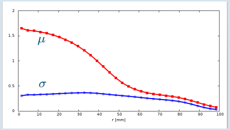


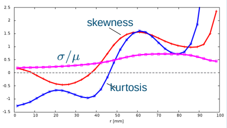
Detailed comparison has been started

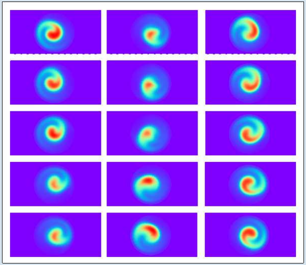
Prototypical Simulations

Simulation parameters have been chosen

as close as possible to NAGDIS-II operational regime





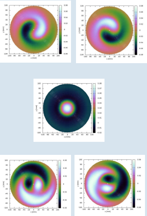


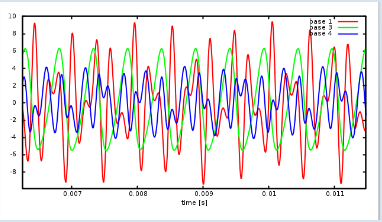
Many similarities with experiment!

Data evaluation

Statistical analysis of time traces

POD approach for detailed pattern analysis



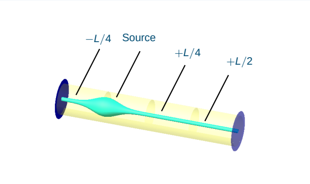


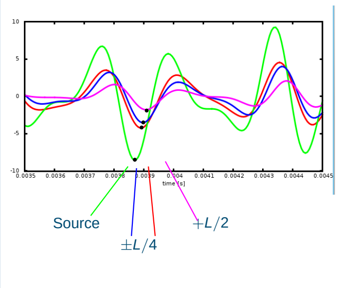
Quasi-periodical process observed

Data evaluation

Statistical analysis of time traces

POD approach for detailed pattern analysis



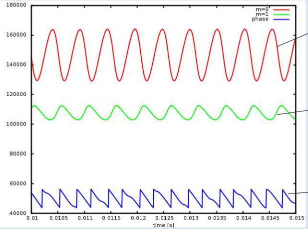


Expulsion starts in source region - propagates with sound speed

Data evaluation

Statistical analysis of time traces

Fourier approach for detailed pattern analysis



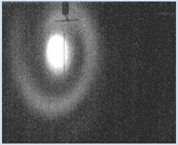
$m = 0$ (prey)

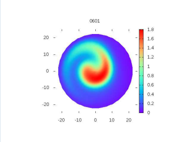
$m = 1$ (predator)

$m = 1$ phase $\Rightarrow$ rotation

Predator-Prey like time traces of poloidal modes

Results of Comparison



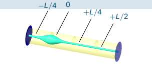


- Spiralling intermittent events
- Dominant POD base modes with $m = 1$ symmetry
- Rotation frequency $\sim$ 3.2 kHz (experiment: 3.4 kHz)
- Expulsion frequency $\sim$ 2.0 kHz (experiment: 3.2 kHz)
- Similar profiles of non-Gaussian statistics

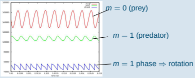
$\boxed{\text{Simulations seem to cover relevant physics}}$

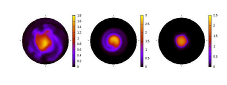
Additional Findings in Simulations

- Perturbation starts in source region



- Quasi-periodic behaviour possible





- Strong impact of radial source shape
- Strong impact of ion-neutral collisions

Is it possible to achieve more from numerical experiments?

The Full 3D Model

Equations for particle, momentum and heat transfer

$$
\begin{aligned}
\frac{\partial n}{\partial t} + \mathbf{v}\cdot\boldsymbol{\nabla} n &= -n\,\boldsymbol{\nabla}\cdot\mathbf{v} \\
m_e\, n\left(\frac{\partial v_\parallel}{\partial t} + \mathbf{v}\cdot\boldsymbol{\nabla} v_\parallel\right) &= -\nabla_\parallel p_e + e\,n\,\eta_\parallel\, J_\parallel + e\,n\,\nabla_\parallel\phi \\
m_i\, n\left(\frac{\partial u_\parallel}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla} u_\parallel\right) &= -\nabla_\parallel p_i - e\,n\,\eta_\parallel\, J_\parallel - e\,n\,\nabla_\parallel\phi \\
\frac{3}{2}\, n\left(\frac{\partial T_e}{\partial t} + \mathbf{v}\cdot\boldsymbol{\nabla} T_e\right) &= -\boldsymbol{\nabla}\cdot\mathbf{q}_e - n\,T_e\,\boldsymbol{\nabla}\cdot\mathbf{v} + \eta_\parallel\, J_\parallel^2
\end{aligned}
$$

and a vorticity equation

$$
\frac{m_i}{eB^2}\left(\frac{\partial \nabla_\perp^2\phi}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla}\nabla_\perp^2\phi\right) = \frac{\nabla_\parallel J_\parallel}{e\,n}
$$

How to identify the most important process and relevant parameters?

Model Reduction I

Inspect numerical dynamics and extract the most important dynamics

$$\frac{\partial n}{\partial t} + \mathbf{V}_E \cdot \boldsymbol{\nabla} n = -\nabla_{\|}(n\, v_{\|}) + \mu_{\perp}\, \nabla_{\perp}^2 n + S_n^e$$

$$\eta_{\|}\, J_{\|} = \frac{T_e\, \nabla_{\|} n}{e\, n} - \nabla_{\|}\phi$$

$$\frac{m_i}{eB^2}\left(\frac{\partial \nabla_{\perp}^2 \phi}{\partial t} + \mathbf{V}_E \cdot \boldsymbol{\nabla}\nabla_{\perp}^2 \phi\right) = \frac{\nabla_{\|} J_{\|}}{en}$$

Focus on single mode perturbations

$$n = n_0(r) + n_m(r)\, e^{im\theta} + n_m(r)^*\, e^{-im\theta} \quad , \quad \phi = \phi_0(r) + \phi_m(r)\, e^{im\theta} + \phi_m(r)^*\, e^{-im\theta}$$

Simplification - but still 2D with parallel dynamics!

Model Reduction II

Now approximate parallel dynamics

$$\frac{\nabla_{\|} J_{\|}}{e\,n} = \frac{1}{e\,n_0\,\eta_{\|}} \left(\frac{\phi}{L_{\phi}^2} - \frac{T_e\,n}{e\,n_0\,L_n^2} \right)$$

Current density replaced by Hasegawa-Wakatani like term

$$\nabla_{\|} \left(n\,v_{\|} \right) = \frac{n\,v_0}{L_v}$$

Parallel electron flow is replaced by a sink

$\boxed{\text{1D model is obtained!}}$

Predator-Prey-Model

Finally one obtains the evolution equations

$$\frac{\partial n_0}{\partial t} = \frac{2\,m}{r}\,\frac{\partial}{\partial r}\left(\mathrm{Im}\left\{n_m\,\phi_m^*\right\}\right) - C_\gamma\,n_0 + \mu_\perp\left(\frac{\partial^2 n_0}{\partial r^2} + \frac{1}{r}\,\frac{\partial n_0}{\partial r}\right) + S_n^e$$

$$\frac{\partial n_m}{\partial t} = \frac{i\,m}{r}\,\frac{\partial n_0}{\partial r}\,\phi_m - \frac{i\,m}{r}\,\frac{\partial \phi_0}{\partial r}\,n_m - C_\gamma\,n_m + \mu_\perp\left(\frac{\partial^2 n_m}{\partial r^2} + \frac{1}{r}\,\frac{\partial n_m}{\partial r} - \frac{m^2}{r^2}\,n_m\right)$$

$$\frac{\partial w_0}{\partial t} = \frac{2\,m}{r}\,\frac{\partial}{\partial r}\left(\mathrm{Im}\left\{w_m\,\phi_m^*\right\}\right) + C_\phi\,\phi_0 - C_n$$

$$\frac{\partial w_m}{\partial t} = \frac{i\,m}{r}\,\frac{\partial w_0}{\partial r}\,\phi_m - \frac{i\,m}{r}\,\frac{\partial \phi_0}{\partial r}\,w_m + C_\phi\,\phi_m - C_n\,\frac{n_m}{n_0}$$

A predator-prey like model has been derived

Three dimensionless parameters for a given configuration

Several features of full 3d modelling are well reproduced

1D predator-prey model allows extensive parameter studies!

Predator-Prey-Model

The physics of the predator-prey cycle

is based on resistive drift wave dynamics

Its model parameters are

$$C_\gamma = \frac{\rho_s\, v_0}{L_\gamma\, c_s} \quad , \quad C_\phi = \frac{m_i\, \rho_s^2\, \omega_i}{m_e\, L_\phi^2\, \nu_e} \quad , \quad C_n = \frac{m_i\, \rho_s^2\, \omega_i}{m_e\, L_n^2\, \nu_e}$$

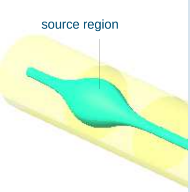
Actually this reflects the parallel structure of the plasma source

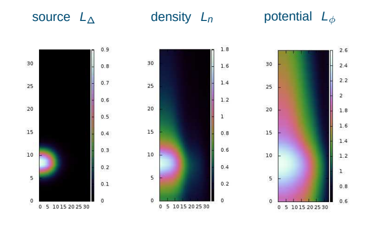
+ a description of the radial structure via source profile $S_n^e(r)$

$$\boxed{\text{The model describes a robust fundamental component of plasma dynamics in the source region}}$$

Predator-Prey-Model

Model parameters L_ϕ, L_n and L_γ are dictated by the source



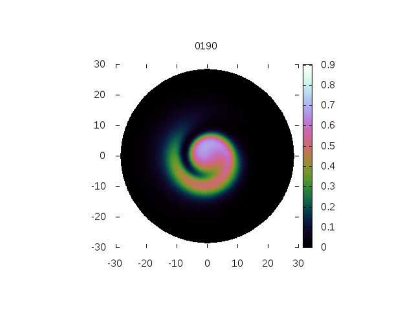


Usually $L_n < L_\phi$!

The model is analyzed with regard to source shape

Predator-Prey-Model

An example for typical numbers from 3D simulation



Nice agreement with Nagdis movie!

Predator-Prey-Model

Too many parameters to explore everything!

Analytical solution not available yet!

But predator-prey model several hundred times faster than 3D simulations!

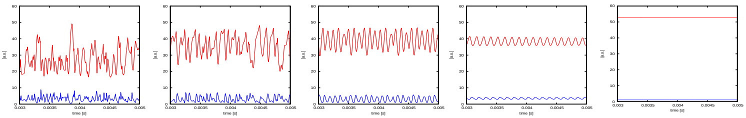
First step: parameters scans over L_n^2/L_ϕ^2, L_n and T_e

Conclusions on qualitative trends possible?

Predator-Prey-Model

Scan L_n^2/L_ϕ^2

0.1	0.2	0.3	0.4	0.5



$\nu_{\mathrm{rot}} \mid \nu_{\mathrm{int}}$ [kHz]

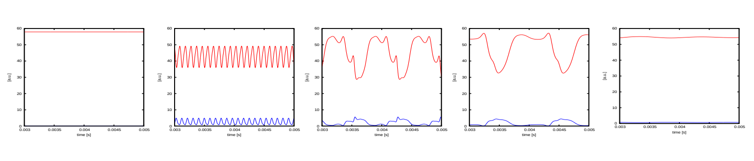
8.0 | ?.?	12.0 | 12.0	15.5 | 11.5	16.5 | 8.5	11.0 | 0.0

$\boxed{\text{Intermittency} \Rightarrow \text{Predator-Prey-Cycle} \Rightarrow \text{Excentric Rotation}}$

Predator-Prey-Model

Parameter scan L_n [m]

0.1 1.0 2.0 2.5 3.0



$\nu_{\mathrm{rot}} \mid \nu_{\mathrm{int}}$ [kHz]

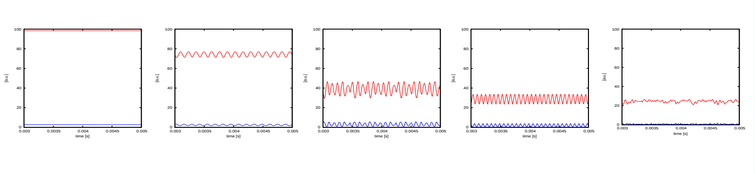
36.5 | 0.0   12.0 | 10.5   5.5 | 1.5   4.5 | 1.0   3.5 | 0.0

Quiet Plasma $\Rightarrow$ Predator-Prey-Cycle $\Rightarrow$ Excentric Rotation

Predator-Prey-Model

Parameter scan T_e [eV]

1.0 1.5 3.0 5.0 10.0



ν_{rot} | ν_{int} [kHz]

5.0 | 0.0 7.0 | 7.5 15.0 | 11.5 ?.? | 14.0 58.0 | ?.?

Excentric Rotation $\Rightarrow$ Predator-Prey-Cycle $\Rightarrow$ Intermittency

Summary of Results

Conclusions and predictions from predator-prey dynamics

- Threshold for intermittency found : $L_n^2/L_\phi^2 < 0.5$.
- Intermittency increasing for decreasing L_n^2/L_ϕ^2.
- A certain window of L_n and T_e shows predator-prey cycles and intermittency.
- For low L_n and low T_e the plasma column becomes quiet.
- High electron temperature enhances intermittencies.
- High electron temperature increases rotation frequency.
- High density gradient increases rotation frequency.

Experimental proof possible?

Summary and Outlook

- Fluid simulations for intermittent dynamics in linear devices continued.
- Several similarities with observations at NAGDIS-II.
- A simplified Predator-Prey-model has been derived for more extensive studies.
- Simple model confirmed by 3D simulations? $\Rightarrow$ partly! Ongoing work!
- Conclusions are to be compared with experimental proof.